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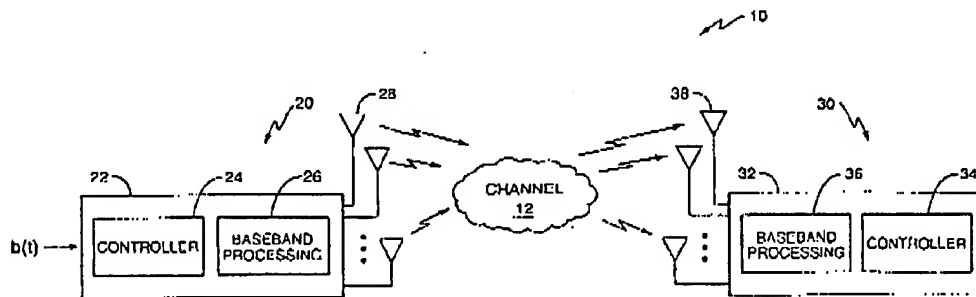
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(54) Title: ADAPTIVE FEEDBACK FOR MIMO COMMUNICATION SYSTEMS



(57) Abstract: An adaptive transmission scheme provides multiple levels of adaptation. At a first level, a selection is made between a limited feedback or open loop scheme and a rich feedback or closed loop scheme. At a second level of adaptation, a diversity mode is selected. Additional levels of adaptation could be employed.

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## ADAPTIVE FEEDBACK FOR MIMO COMMUNICATION SYSTEMS

## BACKGROUND OF THE INVENTION

The present invention relates to multi-antenna transmission schemes for wireless communication networks and more particularly, to an arrangement and a method for adapting between transmitter and receiver configurations responsive to channel conditions and other factors.

In most conventional second generation (2G) and third generation (3G) wireless communication systems, both the transmitter and receiver are equipped with a single antenna. Such systems are known as single input, single output (SISO) systems. In recent years, researchers have proposed using multiple antennas at the transmitter and/or receiver to improve performance of the communication system. Transmit diversity is one example of a multiple antenna transmission scheme that has been proposed as a way of improving the signal-to-interference ratio (SINR) at the receiver. As used herein, SINR includes noise interference. Transmit diversity systems are also known as multiple input, single output (MISO) systems. Transmit diversity or MISO systems employ multiple antennas at the transmitter to transmit a signal to the receiver. The signals from each transmit antenna arrive at the receiver through different propagation channels. The receiver can select the "best" signal (typically the one with the highest SINR), or can combine multiple signals to achieve a higher SINR through combining gain. Transmit diversity using space-time codes further improves the SINR by coding the transmit signal prior to transmission. While transmit diversity schemes realize improvements in the SINR, peak rate improvement is limited to single-antenna modulation and coding options.

Multiple input, multiple output (MIMO) systems employ multiple antennas at the receiver as well as at the transmitter. MIMO systems exploit the spatial dimensions of the signal at the receiver to achieve higher spectral efficiency and higher data rates without increasing bandwidth. The trade-off results in greater complexity of the transmitter and receiver. MIMO systems can be broadly classified as limited feedback (also known as open loop) and rich feedback (also known as closed loop) systems. In limited feedback MIMO systems, only limited information concerning the communication channel is fed back from the receiver to the transmitter. Limited feedback systems improve the attainable peak transfer rate and are more advantageous in high SINR environments. In rich feedback systems, the receiver sends channel coefficients, or other information from which channel coefficients can be estimated, back to the transmitter. The transmitter can use the knowledge of the channel to filter the transmit signal prior to transmission. Rich feedback systems provide additional benefit due to array gain from multiple transmit antennas, which may be substantial for certain array configurations.

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Unfortunately, there is no one system configuration that performs consistently better than the others over the range of possible operating conditions envisioned for deployment. Some of the operating conditions that affect performance include the expected operating SINR at the receiver; the propagation channel and interference environment observed at the receiver; the amount of channel feedback allowed; the assumed user data traffic; and the number of  
5 desired allowable transmit and receive antennas. What is desired is to have a robust approach that works well for different antenna configurations in a wide range of operating conditions.

#### SUMMARY OF THE INVENTION

10 The present invention relates to an adaptive transmission scheme having at least two levels of adaptation. At the first level, the feedback mode is selected based on some quality metric that indicates receiver performance. For example, the metric may be one or more SINRs at the output of the terminal receiver or the supportable data rate by the receiver. This quality metric may depend on a number of measurable quantities, including the number of the receive  
15 antennas, channel quality, mobile speed, the condition of the propagation channel, and/or the available bandwidth between the mobile station and base station. The terminal can calculate this quality metric for closed-loop and open-loop modes and switch to the mode with satisfies the switch criterion. In one exemplary embodiment, the feedback modes include limited feedback or open loop mode and rich feedback or closed loop mode. Transmitter  
20 configurations for limited feedback mode include a per antenna rate control (PARC) and spatial multiplexing (SM) combined with code reuse. In these approaches, a data stream is divided into multiple streams and each substream is transmitted from a different antenna. Transmitter configurations for closed loop mode include matched field transmit diversity (MFTD) in which the data stream is divided into one or more substreams and each substream is prefiltered to match  
25 the channel to a selected receive antenna.

At the second level, a diversity mode is selected. When open loop mode is selected, selection of a diversity mode corresponds to selection of a number of antennas. When less than all transmit antennas are used, the selection may include the "best" subset of antennas. When closed loop mode is selected, the selection of a diversity mode corresponds to selection  
30 of the number of data streams. When the number of data streams is less than the number of receive antennas, the selection may include the subset of receive antennas to which the prefilters are matched. The number of selection levels could also be greater than two, for example, once an open-loop MIMO scheme has been selected, there may be multiple open-loop MIMO schemes from which to choose.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates a multiple input, multiple output communication system.

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Figs. 2 - 4 compare performance of SISO, MISO, and MIMO systems with different antenna configurations.

Fig. 5 illustrates an exemplary open loop transmitter configuration using per antenna rate control.

5 Fig. 6 illustrates an exemplary open loop transmitter configuration using spatial multiplexing with code reuse.

Fig. 7 illustrates an exemplary closed loop transmitter configuration using matched field transmit diversity.

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#### DETAILED DESCRIPTION OF THE INVENTION

Figure 1 illustrates a multiple input/multiple output (MIMO) wireless communication system 10 including a first station 20 and a second station 30. The first station 20 includes a transmitter 22 for transmitting signals to the second station 30, while the second station includes a receiver 32 for receiving signals transmitted by the first station 20. Those skilled in the art will appreciate that the first station 20 and second station 30 may each include both a transmitter 22 and receiver 32 as shown in Fig. 1 for bi-directional communications. In one exemplary embodiment, the first station 20 is a base station in a wireless communication network, and the second station 30 is mobile station.

An information signal in the form of a binary data stream is input to the transmitter 22 at the first station 20. The transmitter includes a controller 24, a transmit signal processing circuit 26, and a plurality of transmit antennas 28. The controller 24 controls operation of the transmitter 22. The transmit signal processing circuit 26 performs error coding and mapping of the input bits to complex modulation symbols. The transmit signal processing circuit 26 generates multiple transmit signals which may be independent, partially redundant, or fully redundant. After upward frequency conversion, filtering, and amplification, the transmit signals are transmitted from respective transmit antennas 28, through the communication channel 12, to the second station 30.

The receiver 32 at the second station 30 includes a controller 34, a receive signal processing circuit 36, and a plurality of antennas 38. The controller 34 controls operation of the receiver 32. The receive signal processing circuit 36 demodulates and decodes the signals received at each antenna 38. In the absence of bit errors, the output signal from the receiver 32 will be the same as the original information signal input at the transmitter 22. Because multiple data streams are transmitted in parallel from different antennas 28, there is a linear increase in throughput with every pair of antennas 28, 38 added to the system without an increase in the bandwidth requirement.

MIMO systems have been the subject of extensive research activity worldwide for use in wireless communication networks because of their potential to achieve high spectral

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efficiencies, and therefore high data rates. Many types of MIMO systems have been proposed, which may be generally classified as either closed loop or open loop. In closed loop MIMO systems, the transmitter receives feedback of channel coefficients from the receiver, which is referred to herein as rich feedback. In open loop MIMO systems, the transmitter receives  
5 limited feedback of channel state information. This limited feedback typically does not include channel coefficients, but may include channel state information such as the SINR of the communication channel.

Closed loop systems, in general, provide improved performance over open-loop systems because such systems have greater knowledge of the communication channel but require  
10 feedback of channel coefficients. The amount of feedback is proportional to the number of transmit antennas, the number of receive antennas, and the channel's delay spread. Figures 2-4 compare the performance of closed loop and open loop multiple antenna systems for a variety of antenna configurations. Fig. 2 compares open loop and closed loop capacity in a 4x1 multiple input, single output (MISO) system. Fig. 3 compares open loop and closed loop  
15 capacity in a 4x2 MIMO system. Fig. 4 compares open loop and closed loop capacity in a 4x4 MIMO system.

In the cellular environment, the channels are random variables; hence, the mutual information corresponding to each transmission scheme is also a random variable with a certain cumulative distribution function (CDF). Figs. 2 – 4 graph the SINR versus the 1% point of the  
20 CDF of the mutual information for various system configurations. This point on the CDF is sometimes referred to as the mutual information resulting in 1% outage probability, i.e. the mutual information of each scheme exceeds the corresponding 1 percentile value with probability of 0.99. The solid curves on these figures correspond to the closed-loop capacity, the dashed curves with stars, "\*", correspond to the open-loop capacity, and the dashed curves with  
25 "x" correspond to a single input, single output (SISO) system with one transmit antenna and one receive antenna.

In the 4x1 MISO system (Fig. 2), closed-loop capacity gains 6 dB over open-loop capacity due to diversity and antenna array gains. Furthermore, the open loop capacity is not much greater than the capacity of the SISO channel over a wide range of operating SINRs. This  
30 indicates that some form of transmit diversity is beneficial in order to obtain increased rates. For a 4x2 MIMO system (Fig. 3), there is still significant gap of approximately 4.5 dB between the closed-loop and open-loop capacity. This is somewhat less than for the 4x1 system, but it still indicates significant performance advantage of the closed loop MIMO system as compared to the open loop MIMO system. For the 4x4 MIMO system (Fig. 4), the gap shrinks to  
35 approximately 3 dB, and occurs mostly at low SINRs.

Exemplary open loop MIMO systems use per antenna rate control (PARC) techniques or spatial multiplexing (SM) techniques combined with code reuse. In the open loop

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configurations, a single input data stream is split into multiple data streams, which are mapped to different transmit antennas. In the PARC approach, described more fully below, each substream is independently coded and modulated. In the SM approach, the input data stream is coded before it is split and the individual substreams are then independently modulated and transmitted. An exemplary closed loop system uses matched field transmit diversity (MFTD), also known as transmit diversity with rich feedback (TDRF), which is described in more detail below. In the closed loop MIMO system using MFTD, the input data stream is transmitted from multiple transmit antennas 28 to a receiver 32 with one or more receive antennas 38. The input stream is pre-filtered to match the channel between the transmit and receive antennas 28, 38.

Fig. 5 illustrates an exemplary transmitter 100 configuration for open-loop mode employing the per antenna rate control (PARC) approach. As those skilled in the art will appreciate, PARC is a multiple stream transmitting technique used in wireless communication systems to increase system capacity. Transmitter 100 in the exemplary embodiment is configured for the High-Speed Downlink Packet Access (HSDPA) mode of WCDMA.

The transmitter 100 in Fig. 5 comprises a demultiplexer 102 to divide the original information bit stream  $I$  into  $M$  bit streams  $\{b_1(t), b_2(t), \dots, b_M(t)\}$ , coding and modulation circuits 104 for each bit stream, and a plurality of antennas 120. The coding and modulation circuit 104 for each bit stream  $\{b_1(t), b_2(t), \dots, b_M(t)\}$  comprises an encoder 106 to encode each bit stream  $\{b_1(t), b_2(t), \dots, b_M(t)\}$ , a plurality of demultiplexers 108 to further divide each bit stream  $\{b_1(t), b_2(t), \dots, b_M(t)\}$  into substreams, a plurality of symbol mappers 110 to map each substream to a point on a signaling constellation, a plurality of signal spreaders 112 to apply a selected spreading code to each substream, and a combiner 114 to recombine the sub-streams to generate a transmit signal  $\{x_1(t), x_2(t), \dots, x_M(t)\}$  for transmission. The transmit signals  $\{x_1(t), x_2(t), \dots, x_M(t)\}$  may be further combined by combiner 116 with one or more other simultaneously transmitted signals  $d_m(t)$  that contain a number of dedicated channels and control channels, as well as a common pilot channel. The encoders 106 for each bit stream  $\{b_1(t), b_2(t), \dots, b_M(t)\}$  encode the original information bits at different rates. The rates depend on the channel quality indicator (CQI) feedback from the receiver 32. The coded signal output by each encoder 106 is then divided into  $K$  substreams by demultiplexers 108. Each substream is mapped to symbols by one of  $K$  symbol mappers 110, and spread with one of  $K$  spreading codes by signal spreaders 112. The  $K$  spreading codes may be reused on the different antennas 120. The combiner recombines the  $K$  spread signals from each signal spreader 112. In Fig. 5, the number of coded signals and the number of transmit antennas 120

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are the same. However, in other embodiments, the number of coded signals could be equal to or fewer than the number of transmit antennas 120.

Fig. 6 illustrates an exemplary transmitter configuration 50 for open-loop mode employing spatial multiplexing (SM) with code reuse. The transmitter configuration 150 shown in Figure 6 comprises an encoder 152 to encode the original information stream  $I$  to generate a coded bitstream, a demultiplexer 154 to divide the coded bitstream into  $N$  bitstreams  $\{b_1(t), b_2(t), \dots, b_M(t)\}$ , modulation circuits 156 for each bitstream, and a plurality of antennas 168. The modulation circuit 156 for each bitstream comprises a demultiplexer 158 to further divide each substream into a larger number of substreams, a plurality of symbol mappers 160 to map each substream to a point on a signaling constellation, a plurality of signal spreaders 162 to apply a selected spreading code to each substream, and a combiner 164 to recombine the substreams to generate a transmit signal  $\{x_1(t), x_2(t), \dots, x_M(t)\}$  for transmission to the second station 30. The transmit signals  $\{x_1(t), x_2(t), \dots, x_M(t)\}$  may be further combined by combiner 166 with one or more other simultaneously transmitted signals  $d_m(t)$  that contain a number of dedicated channels, control channels, as well as a common pilot channel.

Fig. 7 illustrates an exemplary transmitter configuration 200 for a closed-loop mode system. The transmitter 200 of Fig. 7 employs what is referred to herein as a matched field transmit diversity (MFTD). The transmitter configuration 200 shown in Fig. 7 includes a demultiplexer 202 to divide the information bitstream into a plurality of bitstreams, a coding and modulation circuit 204 for each bitstream, a prefilter 212 matched to the communication channel between the transmitter and the receiver, and a plurality of transmit antennas 214. Each coding and modulation circuit 204 includes an encoder 206 to encode a corresponding bitstream, a symbol mapper 208 to map the coded bits to modulation symbols, and a signal spreader 210 to apply a selected spreading code to each substream. The signals output from the modulation and encoding circuits 204 are the transmit signals  $s_1(t), \dots, s_N(t)$  to be transmitted to the second station 30, where  $N$  is less than or equal to the number of antennas at the receiver 32. The transmit signals  $s_1(t), \dots, s_N(t)$  are input to a prefilter 212. The prefilter filters the transmit signals based on knowledge of the communication channel between the transmitter 22 and the receiver 32. The prefilter outputs filtered signals  $x_1(t), \dots, x_M(t)$  to the antennas 214 for transmission to the second station 30, where  $M$  is the number of transmit antennas 214.

The following discussion explains how the filters for the prefilter 212 are computed. It is assumed that the signals  $s_1(t), \dots, s_N(t)$  input to the prefilter 212 are mutually independent and each one has a power spectrum  $\Lambda(f)$  within the channel bandwidth. The power spectrum of



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the transmit signal vector  $\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_N(t)]$  is denoted by  $\mathbf{P}_{\mathbf{s}}(f)$ . The power spectrum of the filtered signal vector  $\mathbf{x}(t)$  may be expressed in terms of  $\mathbf{P}_{\mathbf{x}}(f)$  according to:

$$P_{\mathbf{x}}(f; m, p) = \Lambda(f) \sum_{n=1}^N G(f; n, m) G^*(f; n, p) \quad \text{Eq. (1)}$$

where  $\Lambda(f)$  is a real-valued function chosen to ensure that the total power emitted from the

5 transmitter is fixed, and  $G(f; n, m)$  is the frequency response of the downlink channel from the  $m$ th transmit antenna to the  $n$ th receive antenna.

As seen in Fig. 7, the MFTD transmitter 200 consists of  $N$  parallel data streams or subchannels and  $M$  antennas 214. Each of the  $N$  parallel data streams have two parts: 1) a modulation and coding circuit 204 that maps information bits to scalar-valued waveforms, and 2) a single input, multiple output bank of matched filters that form a part of prefilter 212. Denoting these matched filters by  $H(f; n, m)$ , then the filters may be represented by

$$H(f; n, m) = \frac{G^*(f; n, m)}{\sqrt{\sum_{n=1}^N \sum_{m=1}^M |G(f; n, m)|^2}} \quad \text{Eq. (2)}$$

The filters given by Eq. 2 have several interesting properties. First, their frequency response is a product of two terms. The first term  $G^*(f; n, m)$  in the numerator is a filter matched to the downlink channel between the  $m$ th transmit antenna and the  $n$ th receive antenna. The second term  $\sqrt{\sum_{n=1}^N \sum_{m=1}^M |G(f; n, m)|^2}$  in the denominator may be viewed as a whitening filter for the information signal. Secondly, Eq. 2 results in a loose form of water pouring in the following sense. If one of the downlink channels at a particular frequency is severely attenuated, the power out of the corresponding transmit antenna 214 will also be proportionally attenuated at this frequency. With the total power out of the antenna 214 being constant, the transmitter 200 will then pour more power into those frequencies where the downlink channels are not attenuated.

A simplification can be obtained by ignoring the frequency depending term

25  $\sqrt{\sum_{n=1}^N \sum_{m=1}^M |G(f; n, m)|^2}$  in the denominator. This approximation leads to the following form of the pre-filters 212:

$$H(f; n, m) = \lambda G^*(f; n, m) \quad \text{Eq. (3)}$$

where  $\lambda$  is a scale factor chosen to ensure that the total transmitted power is  $\sigma_X^2$ , i.e.

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$$\lambda = \frac{\sigma_x}{\sqrt{\sum_{n=1}^N \sum_{m=1}^M \int |G(f; n, m)|^2 df}} \quad \text{Eq. (4)}$$

Implementation of the filters given by Equation 3 is very simple; since, the impulse response of  $G^*(f; n, m)$  is simply  $g^*(-t; n, m)$ . This implies that the filters can be implemented in transmitter 200 by a simple FIR filter matched to the original downlink channel. Based on this observation, the downlink-channel from the  $m$ -th transmit antenna 214 to the  $n$ -th receive antenna 38 may be modeled as:

$$g(t; n, m) = \sum_{k=1}^K \alpha_k(n, m) \delta(t - \tau_k) \quad \text{Eq. (5)}$$

Then the impulse response of the  $m$ -th filter in the  $n$ -th sub-channel has the form

$$h(t; n, m) = \lambda \sum_{k=1}^K \alpha_k^*(n, m) \delta(t + \tau_k) \quad \text{Eq. (6)}$$

A base station with the transmitter structure of Fig. 7 needs only to form these matched filters based on the knowledge of the downlink channels available at the base station.

To reduce the amount of feedback overhead for MFTD scheme, matched filters  $h(t; n, m)$  based on only partial channel state information may be used. The idea of the MFTD scheme is based on using suboptimal FIR pre-filters with limited number of taps. The coefficients  $\hat{\alpha}_k^*(n, m)$  for these pre-filters can be chosen to equal the  $L$  strongest channel coefficients or can be chosen based on the fixed-grid approach, where a grid of evenly-spaced  $L$  fingers is placed on a "region" of signal energy indicated by the power/delay profile, and where  $L$  is less than or equal to the number of channel coefficients. With this simplified approach, the impulse response of the  $m$ -th filter in the  $n$ -th sub-channel has the form

$$\hat{h}(t; n, m) = \bar{\lambda} \sum_{k=1}^L \hat{\alpha}_k^*(n, m) \delta(t + \tau_k) \quad \text{Eq. (7)}$$

This MFTD scheme allows the reduction of the amount of feedback and at the same time achieves most of the closed-loop capacity of dispersive channels. The proposed MFTD transmitter configuration can also operate with  $N_c$  multicodes which are reused on each transmit antenna. The multicodes are reused to avoid excessive consumption of code resources when transmitting with multiple antennas.

According to the present invention, the transmitter 20 can be configured for a closed loop or rich feedback mode of operation, and a limited feedback or open-loop mode of operation at different times based on the expected performance of the receiver in each feedback mode. Factors relevant to determining the expected performance include the channel parameters, code and power availability, receiver antenna configuration, and operating conditions. In

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general, closed loop mode is selected when the increase in the expected performance of closed-loop mode over open-loop mode justifies the additional overhead required to feedback channel coefficients. For the open loop mode, the transmitter configurations shown in Figs. 5 and/or 6 may be used. For the closed loop mode, the transmitter configuration shown in Fig. 7 may be used.

The feedback mode can be changed during transmission as conditions change based on one or more quality metrics indicative of the expected performance of the receiver. For example, one quality metric may be the SINR at the output of the receiver 32 or the supportable data rate of the receiver 32. The quality metric may depend on a number of factors including the number of receive antennas 38, mobile station speed or velocity, and channel conditions. Thus, in the present invention the feedback mode is adapted as the operating conditions change to maximize performance.

Additional levels of adaptation can be employed in addition to the adaptation of the feedback mode. For example, a selection may be made between the two different open loop modes shown in Figs. 5 and 6. Additionally, a diversity mode may be selected after the feedback mode is selected. The selection of a diversity mode may depend, for example, on channel parameters, code availability, and power availability.

When an open-loop mode is selected, the various diversity modes correspond to different antenna configurations at the transmitter 22. Thus, selection of the diversity mode means the selection of the number of antennas 28 and which antennas 28 to use for transmission to the mobile station 30 giving rise to a selective PARC (S-PARC) scheme (Fig. 5) or a selective spatial multiplexing coding (S-SM) scheme (Fig. 6). When closed-loop mode is selected, the various diversity modes correspond to different pre-filter configurations. Thus, selection of the diversity mode means selection of the number of pre-filters 212 or data streams at the transmitter 22 and selection of the number of receive antennas 38 at the receiver 32 to which the pre-filters 212 are matched giving rise to a selective MFTD (S-MFTD) scheme.

In one exemplary embodiment described below, the diversity mode for an open loop feedback mode is selected based on the expected SINR or supportable data rate at the receiver 32. Both S-PARC and S-SM will be elaborated further below using the High-Speed Downlink Packet Access (HSDPA) provision in the Wideband Code Division Multiple Access (W-CDMA) standard as an example. The discussion below considers the case of two transmit antennas 28. The possible antenna configurations are {A}, {B}, or {A, B}. We will also add an additional case of {B, A} for S-PARC. Here the ordering indicates the decoding order of the receiver operation of S-PARC. For S-PARC, decoding order might have a small impact on the supportable data rate in dispersive channels. Thus, it may be advantageous, as far as maximizing the achievable data rate is concerned, to consider different decoder ordering for a given antenna combination. However, in most channel conditions, the difference between the achievable data rates of {A, B}

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and  $\{B, A\}$  is very small, and thus to minimize complexity, it might be advantageous to consider only one decoder ordering for a given antenna combination.

For S-PARC, an active antenna 28 transmits one self-decodable data stream. The transmission rate of a data stream is determined by the symbol signal-to-interference-plus-noise ratio (SINR), indicative of receiver performance. In the discussion below, we will use SIC-  
5 GRAKE output SINR as an example. The SIC-GRAKE is described in co-pending US Patent Application Serial No. 00/795,101 filed March 5, 2004, which is incorporated herein by reference.

It is assumed that all available power is allocated evenly among all active transmit  
10 antennas 28. For antenna configuration  $\{A\}$ , all the available power  $P$  is allocated to transmit antenna  $A$ , resulting in power per channelization code as  $P/K$ , where  $K$  is the number of channelization codes. Since there is only one active antenna 28, there is no need to perform successive interference cancellation (SIC) after G-RAKE. In this case, G-RAKE output SINR can be shown as

$$15 \quad \text{SINR}_{\{A\}}(A) = \frac{P}{K} h(A)^H R_{\{A\}}^{-1}(A) h(A), \quad \text{Eq. (8)}$$

where  $h(A)$  is the net response corresponding to the channel associated with antenna  $A$  and  $R_{\{A\}}(A)$  is the noise covariance. The subscript to noise covariance denotes that the noise covariance depends on the antenna configuration. In practice, in this case, both the net response and the noise covariance can be determined from measurements on the Common  
20 Pilot Channel. The relation  $R_{\{A\}}(A) = R_{\text{CPICH}}(A)$  denotes that the noise covariance can be measured from the Common Pilot Channel. The supportable data rate can then be determined by the G-RAKE output SINR through a table-lookup or through a SINR-to-data-rate mapping function,

$$\text{Rate}(\{A\}) = f(\text{SINR}_{\{A\}}(A)) \quad \text{Eq. (9)}$$

25 Similarly, for antenna configuration  $\{B\}$ , the G-RAKE output SINR can be shown as,

$$\text{SINR}_{\{B\}}(B) = \frac{P}{K} h(B)^H R_{\{B\}}^{-1}(B) h(B), \quad \text{Eq. (10)}$$

where  $h(B)$  is the net response corresponding to the channel associated with antenna  $B$  and  $R_{\{B\}}(B)$  is the noise covariance. Again, in this case, both the net response and the noise covariance can be measured from the Common Pilot Channel. The relation

30  $R_{\{B\}}(B) = R_{\text{CPICH}}(B)$  denotes that the noise covariance can be measured from the Common Pilot Channel. There are cases where  $R_{\text{CPICH}}(A) = R_{\text{CPICH}}(B)$ . The supportable data rate for this case is

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$$Rate(\{B\}) = f(SINR_{iB}(B)). \quad \text{Eq. (11)}$$

For antenna configuration  $\{A, B\}$ , each antenna is allocated with power  $P/2$ ; the antenna  $A$  signal will be decoded first and the antenna  $B$  signal will be decoded last. In this case, the G-RAKE output  $SINR$  for antenna  $A$  signal is

$$5 \quad SINR_{iA,B}(A) = \frac{P}{2K} h(A)^H R_{iA,B}^{-1}(A) h(A), \quad \text{Eq. (12)}$$

where the noise covariance becomes  $R_{iA,B}(A) = R_{CPICH}(A) + \frac{P}{2K} h(B) h^H(B)$ . The additional term on the right-hand side of the equation accounts for the code-reuse interference, resulting from the same channel code being used for transmitting the antenna  $B$  signal.

For antenna  $B$  signal, SIC will be used, as the G-RAKE output  $SINR$  reflecting SIC is

$$10 \quad SINR_{iA,B}(B) = \frac{P}{2K} h(B)^H R_{iA,B}^{-1}(B) h(B), \quad \text{Eq. (13)}$$

where the noise covariance is  $R_{iA,B}(B) = R_{CPICH}(B) - \frac{P}{2} R_{SC}(A)$ . The second term on the right-hand side of the equation accounts for interference from antenna  $A$  signal that is removed by the SIC process. The supportable data rate for this antenna configuration can be determined by

$$Rate(\{A, B\}) = f(SINR_{iA,B}(A)) + f(SINR_{iA,B}(B)) \quad \text{Eq. (14)}$$

15 Similarly, for antenna configuration  $\{B, A\}$ , the G-RAKE output  $SINR$  for antenna  $B$  signal is  $SINR_{iB,A}(B) = \frac{P}{2K} h(B)^H R_{iB,A}^{-1}(B) h(B)$ , where the noise covariance becomes

$$R_{iB,A}(B) = R_{CPICH}(B) + \frac{P}{2K} h(A) h^H(A). \quad \text{Eq. (15)}$$

For antenna  $A$  signal, the G-RAKE output  $SINR$  reflecting SIC is

$$SINR_{iB,A}(A) = \frac{P}{2K} h(A)^H R_{iB,A}^{-1}(A) h(A), \text{ where the noise covariance is}$$

20  $R_{iB,A}(A) = R_{CPICH}(A) - \frac{P}{2} R_{SC}(B)$ . The supportable data rate for this antenna configuration can be determined by

$$Rate(\{B, A\}) = f(SINR_{iB,A}(B)) + f(SINR_{iB,A}(A)). \quad \text{Eq. (16)}$$

25 With the supportable data rate for each of the antenna configurations, the base station controller 24 or mobile station controller 34 can choose the one having the highest achievable data rate. It can be seen in the above example that, the calculation of supportable data rate depends on power allocation ( $P$ ), code allocation ( $K$ ), and channel parameters

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$(h(A), h(B), R_{\{A\}}(A), R_{\{B\}}(B), R_{\{A,B\}}(A), R_{\{A,B\}}(B), R_{\{A,B\}}(A), R_{\{A,B\}}(B))$ . Those skilled in the art will find that this easily generalizes to the case of having more than two transmit antennas 28.

For selective spatial multiplexing code, the same procedure as described earlier for S-PARC applies. The only difference is the *SINR* formulation and the *SINR*-to-data-rate mapping function for antenna configurations  $\{A, B\}$ . The achievable data rate for antenna configurations  $\{A\}$ , and  $\{B\}$  of S-SM are exactly the same as those for S-PARC. Thus, we will only discuss the case of  $\{A, B\}$ .

The *SINRs* at the G-RAKE output in this case are

$$SINR_{\{A,B\}}(A) = \frac{P}{2K} h(A)^H R_{\{A,B\}}^{-1}(A) h(A), \quad \text{Eq. (17)}$$

10

and

$$SINR_{\{A,B\}}(B) = \frac{P}{2K} h(B)^H R_{\{A,B\}}^{-1}(B) h(B), \quad \text{Eq. (18)}$$

where the noise covariances are  $R_{\{A,B\}}(A) = R_{CPKCH}(A) + \frac{P}{2K} h(B)h^H(B)$  and

$$R_{\{A,B\}}(B) = R_{CPKCH}(B) + \frac{P}{2K} h(A)h^H(A). \text{ One method for determining the achievable data rate}$$

is based on the sum of the individual *SINR* values, and is given as

$$Rate(\{A, B\}) = f(SINR_{\{A,B\}}(A)) + f(SINR_{\{A,B\}}(B)). \quad \text{Eq. (19)}$$

Other methods may also be considered, such as those based on the geometric (rather than arithmetic) mean. With the supportable data rate for each of the antenna configurations, the base station controller 24 or mobile station controller 34 can choose the one having the highest achievable data rate. In can be seen in the above example that, the calculation of supportable data rate depends on power allocation (*P*), code allocation (*K*), and channel parameters  $(h(A), h(B), R_{\{A\}}(A), R_{\{B\}}(B), R_{\{A,B\}}(A), R_{\{A,B\}}(B))$ .

The decision making for the determination of the diversity mode for open loop transmitter configurations can be made at the mobile station 30, at the base station 20, or are divided between the base station 20 and mobile station 30. In the first approach (all decisions made at the mobile station 30), the mobile station 30 estimates the *SINRs* for all possible antenna combinations and chooses that particular combination that results in the maximum sum data rate over substreams. It then feeds back a rate indicator, or CQI (Channel Quality Indicator) for each stream, i.e., if mode-*N* is selected where *N* is the selected number of antennas, then *N* CQIs are signaled back where  $N \leq M$ . The CQI is typically a mapping from *SINR* to data rate. It also needs to signal the antenna selection from the  $2^M - 1$  possibilities, requiring *M* bits.

In the second approach (all decisions made at the base station 20), the mobile station 30 estimates the *SINRs* for all possible mode and antenna selection combinations. However,

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because no decision is made at the mobile station 30 as to which is the best one, the mobile station 30 must feedback CQI values for all possible combinations leading to very large feedback load. For example, for s-parc with 4 transmit antennas 28, the mobile station 30 would need to feedback one CQI for each of the 4 mode-1 antenna selections, 2 CQIs for each of the 5 6 mode-2 antenna selections, 3 CQIs for each of the 4 mode-3 antenna selections, and 4 CQIs for the single mode-4 selection, resulting in a total of 32 CQI values. This is compared to the first approach where the feedback load is 4 or fewer CQIs and one antenna selection indicator. As such, allowing the base station 20 to have full freedom to do both mode and antenna selection requires a large amount of feedback.

10 In the third approach (division of decision making between mobile station 30 and base station 20), the mobile station 30 selects the antennas for each possible mode, and the base station 20 selects the mode. In this way, the feedback is reduced significantly as compared to the second approach. In fact, if the antenna selections are restricted to obey a certain property (called the subset property) the feedback may be reduced to a level only slightly greater than 15 the first approach. While this approach is suboptimal, the loss in performance is small. Without using the subset property, however, the feedback load for the example of  $M = 4$  transmit antennas would be 1 CQI for mode-1, 2 CQIs for mode-2, 3 CQIs for mode-3, and 4 CQIs for mode-4, resulting in a total of 10 CQIs. In addition, an antenna selection indicator would be required for each mode. Clearly, the required feedback load is much less than the second 20 approach, which requires 32 CQIs.

As explained in UK Patent No. 2358071 issued on April 2, 2003 which is incorporated by reference in its entirety, if the subset property is invoked, the feedback load may be reduced to only  $M = 4$  CQIs and one decoding order. This is only slightly more than the maximum feedback load for the first approach, which requires  $N = 4$  CQIs (when mode-4 is selected) and one 25 antenna selection indicator. The decoding order is a permutation of  $M$  integers, and indicates in which order the streams should be decoded for each possible mode. Because there are  $M!$  possible decoding orders, the feedback of the decoding order requires slightly more bits than simply an antenna selection indicator. For example, with  $M = 4$ , the decoding order requires  $\text{ceil}(\log_2(M!)) = 5$  bits in contrast to the antenna selection indicator which requires only 30  $\text{ceil}(\log_2(2^M - 1)) = 4$  bits. SINR estimation and feedback can be done in a similar manner for SM with the only difference being that one CQI is estimated and fed back for each antenna combination.

The concept of diversity mode selection can also be applied to the closed loop transmitter configuration shown in Fig. 7. According to the present invention, the number of 35 data streams is changed adaptively as conditions change. Each data stream uses a set of sub-optimal filters given in Eq. 7. Further, depending on channel conditions, the "best" subset set of

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streams which are to be transmitted is selected, which is a type of channel selection. One interpretation of "best" is the subset of transmitted streams that supports the largest rate.

The selection of the diversity mode can be made by either the mobile station controller 34 or the base station controller 24. In the first instance, the mobile estimates the SINRs for all possible combinations of the transmitted data streams and chooses that particular combination that results in the maximum sum data rate. It then feeds back a CQI for each stream and corresponding set of the channel coefficients. For example, if mode-N is selected, then N CQIs and  $(M \times L \times N)$  channel coefficients are transmitted back, where M is the number of transmit antennas 28 and L is the number of taps of the transmitter pre-filters 212. It should be mentioned that  $N \leq N_{RX}$ , where  $N_{RX}$  is the number of receive antennas 38. In the second instance, the mobile feeds back  $(M \times L \times N_{RX})$  channel coefficients. In some situations, the power of other-cell interference would be required to feedback to the base station.

The present invention may, of course, be carried out in other specific ways than those herein set forth without departing from the scope and essential characteristics of the invention. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.



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## CLAIMS

1. A method of transmitting signals between a base station and a mobile station in a wireless communication network, the method comprising:  
selecting a desired feedback mode to be one of a rich feedback mode and a limited  
5 feedback mode based on an expected performance at a mobile station; and  
configuring a base station transmitter based on the desired feedback mode.
2. The method of claim 1 wherein selection of a desired feedback mode is based at least in part on mobile station capability.
- 10 3. The method of claim 1 wherein selection of a desired feedback mode is based at least in part on mobile station speed or velocity.
4. The method of claim 1 wherein selection of a desired feedback mode is based at least in part on available bandwidth between the mobile station and the base station.
- 15 5. The method of claim 1 wherein selection of a desired feedback mode is based at least in part on past performance of the mobile station in said rich feedback and limited feedback modes.
- 20 6. The method of claim 1 wherein selection of a desired feedback mode is based at least in part on characteristics of the communication channel between the base station and the mobile station.
- 25 7. The method of claim 1 wherein configuring a base station transmitter based on the desired feedback mode comprises configuring the base station transmitter to use per antenna rate control if the limited feedback mode is selected.
8. The method of claim 7 further comprising selecting a diversity mode and configuring the  
30 base station transmitter for the selected diversity mode.
9. The method of claim 8 wherein selecting a diversity mode comprises selecting a number of transmit antennas to use for transmission to said mobile station.
- 35 10. The method of claim 9 wherein selecting the diversity mode further comprises selecting a subset of a set of transmit antennas to use for transmission to the mobile station, wherein

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configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.

11. The method of claim 9 further comprising receiving an antenna selection from the mobile station indicating a subset of antennas to use for transmission to the mobile station, wherein configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.

12. The method of claim 7 further comprising receiving from the mobile station a diversity mode signal indicating a selected diversity mode and configuring the base station transmitter for the selected diversity mode.

13. The method of claim 12 further comprising receiving an antenna selection from the mobile station indicating a subset of selected antennas to use for transmission to the mobile station, wherein configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.

14. The method of claim 1 wherein configuring a base station transmitter based on the desired feedback mode comprises configuring the base station transmitter to use a spatial multiplexing coding scheme if the limited feedback mode is selected.

15. The method of claim 14 further comprising selecting a diversity mode and configuring the base station transmitter for the selected diversity mode.

16. The method of claim 15 wherein selecting a diversity mode comprises selecting a number of transmit antennas to use for transmission to said mobile station.

17. The method of claim 16 wherein selecting the diversity mode further comprises selecting a subset of a set of transmit antennas to use for transmission to the mobile station, wherein configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.

18. The method of claim 16 further comprising receiving an antenna selection from the mobile station indicating a subset of antennas to use for transmission to the mobile station, wherein configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.

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19. The method of claim 14 further comprising receiving from the mobile station a diversity mode signal indicating a selected diversity mode and configuring the base station transmitter for the selected diversity mode.
- 5 20. The method of claim 19 further comprising receiving an antennas selection from the mobile station indicating a subset of selected antennas to use for transmission to the mobile station, wherein configuring the base station transmitter for the selected diversity mode comprises configuring the base station transmitter to use the selected antennas.
- 10 21. The method of claim 1 wherein configuring a base station transmitter based on the desired feedback mode comprises configuring the base station transmitter to use matched field processing transmit diversity if rich feedback mode is selected.
22. The method of claim 21 further comprising selecting a diversity mode based on channel  
15 information feedback from the mobile station and configuring the base station transmitter for the selected diversity mode.
23. The method of claim 22 wherein selecting a diversity mode comprises selecting a  
20 number of data streams to transmit to the mobile station based on said channel information feedback.
24. The method of claim 23 wherein said channel information feedback includes channel  
25 coefficients for one or more propagation channels from the base station transmitter to the mobile station.
25. The method of claim 24 wherein configuring the base station transmitter includes  
configuring a prefilter for each data stream based on said channel coefficients.
26. The method of claim 25 wherein each prefilter is configured to match a propagation  
30 channel from all transmit antennas to a selected receive antenna at the mobile station.
27. The method of claim 21 further comprising receiving a diversity mode selection from the  
mobile station indicating a selected diversity mode and configuring the base station transmitter  
for the selected diversity mode.
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28. The method of claim 27 wherein the diversity mode selection indicates the number of data streams to transmit to the mobile station, and wherein configuring the base station transmitter includes configuring a prefilter for each data stream.
- 5 29. The method of claim 28 wherein each prefilter is configured to match a propagation channel from one or more selected transmit antennas to a selected receive antenna at the mobile station.
30. A base station comprising:  
10 a transmitter having a plurality of transmit antennas; and  
a transmission control circuit operatively coupled to the transmitter for selecting a desired feedback mode to be one of a rich feedback mode and a limited feedback mode, and for configuring said transmitter based on the desired feedback mode.
- 15 31. The base station of claim 30 wherein the transmission control circuit selects a desired feedback mode based at least in part on mobile station capability.
32. The base station of claim 30 wherein the transmission control circuit selects a desired  
20 feedback mode based at least in part on mobile station speed or velocity.
33. The base station of claim 30 wherein the transmission control circuit selects a desired feedback mode based at least in part on past performance of the mobile station in said rich feedback and limited feedback modes.
- 25 34. The base station of claim 30 wherein the transmission control circuit selects a desired feedback mode based at least in part on characteristics of the communication channel between the base station and the mobile station.
- 30 35. The base station of claim 30 wherein the transmission control circuit configures the transmitter to use per antenna rate control if the limited feedback mode is selected.
36. The base station of claim 35 wherein the transmission control circuit further selects a diversity mode and configures the base station transmitter for the selected diversity mode.
- 35 37. The base station of claim 36 wherein the transmission control circuit selects a diversity mode by selecting a number of transmit antennas to use for transmission to said mobile station.

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38. The base station of claim 37 wherein the transmission control circuit selects a diversity mode by selecting a subset of a set of transmit antennas to use for transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas.

39. The base station of claim 36 further comprising a receiver to receive an antenna selection from the mobile station indicating a subset of selected antennas to use for transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas.

40. The base station of claim 35 further comprising a receiver to receive a diversity mode selection from a mobile station indicating a selected diversity mode, wherein the transmission control circuit configures the transmitter for the selected diversity mode responsive to receipt of the diversity mode selection from the mobile station.

41. The base station of claim 40 within the receiver receives an antenna selection indicating a subset of selected antennas to use for transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas responsive to receipt of the antenna selection from the mobile station.

42. The base station of claim 30 wherein the transmission control circuit configures the transmitter to use a spatial multiplexing coding scheme if the limited feedback mode is selected.

43. The base station of claim 42 wherein the transmission control circuit further selects a diversity mode and configures the base station transmitter for the selected diversity mode.

44. The base station of claim 43 wherein the transmission control circuit selects a diversity mode by selecting a number of transmit antennas to use for transmission to said mobile station.

45. The base station of claim 44 wherein the transmission control circuit selects a diversity mode by selecting a subset of a set of transmit antennas to use for transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas.

46. The base station of claim 43 further comprising a receiver to receive an antenna selection from the mobile station indicating a subset of selected antennas to use for

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transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas.

5 47. The base station of claim 42 further comprising a receiver to receive a diversity mode selection from a mobile station indicating a selected diversity mode, wherein the transmission control circuit configures the transmitter for the selected diversity mode responsive to receipt of the diversity mode selection from the mobile station.

10 48. The base station of claim 47 within the receiver receives an antenna selection indicating a subset of selected antennas to use for transmission to the mobile station, wherein the transmission control circuit configures the transmitter to use the selected antennas responsive to receipt of the antenna selection from the mobile station.

15 49. The base station of claim 30 wherein the transmission control circuit configures the transmitter to use matched field processing transmit diversity if rich feedback mode is selected.

20 50. The base station of claim 49 wherein the transmission control circuit selects a diversity mode based on channel information feedback from the mobile station and configures the base station transmitter for the selected diversity mode.

51. The base station of claim 50 wherein the transmission control circuit selects a diversity mode by selecting a number of data streams to transmit to the mobile station based on said channel information feedback.

25 52. The base station of claim 51 wherein said channel information feedback includes channel coefficients for one or more propagation channels from the transmitter to the mobile station.

30 53. The base station of claim 51 wherein the transmission control circuit configures the transmitter by configuring a prefilter for each data stream based on said channel information feedback.

35 54. The base station of claim 53 wherein the transmission control circuit configures each prefilter to match a propagation channel from all transmit antennas to a selected receive antenna at the mobile station.

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55. The base station of claim 49 further comprising a receiver to receive a diversity mode selection from the mobile station indicating a selected diversity mode, wherein the transmission control circuit configures the station transmitter for the selected diversity mode responsive to receipt of a diversity mode selection from the mobile station.

5

56. The base station of claim 55 wherein the diversity mode selection indicates the number of data streams to transmit to the mobile station, and wherein configuring the base station transmitter includes configuring a prefilter for each data stream.

10 57. The base station of claim 56 wherein each prefilter is configured to match the channel to a selected receive antenna at the mobile station.

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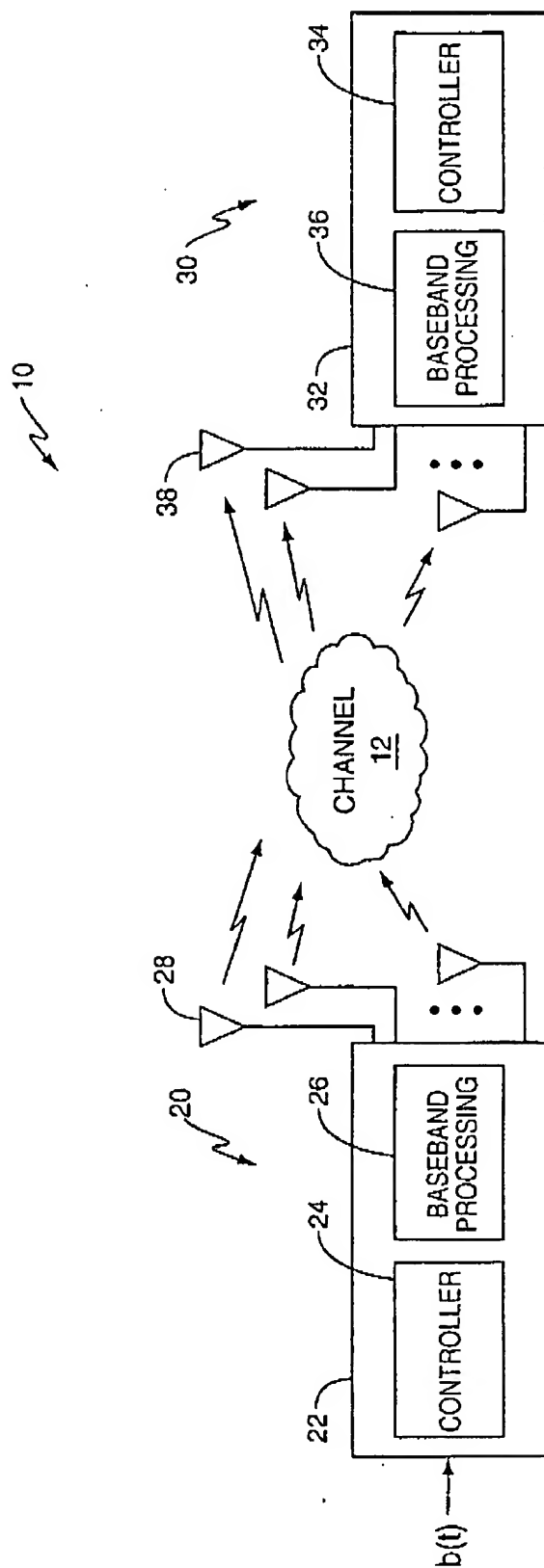


FIG. 1



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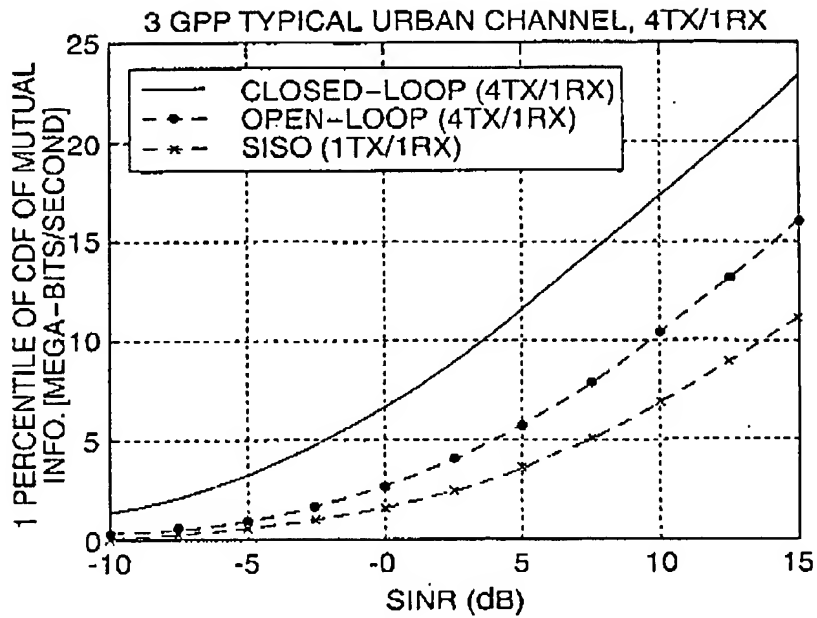


FIG. 2

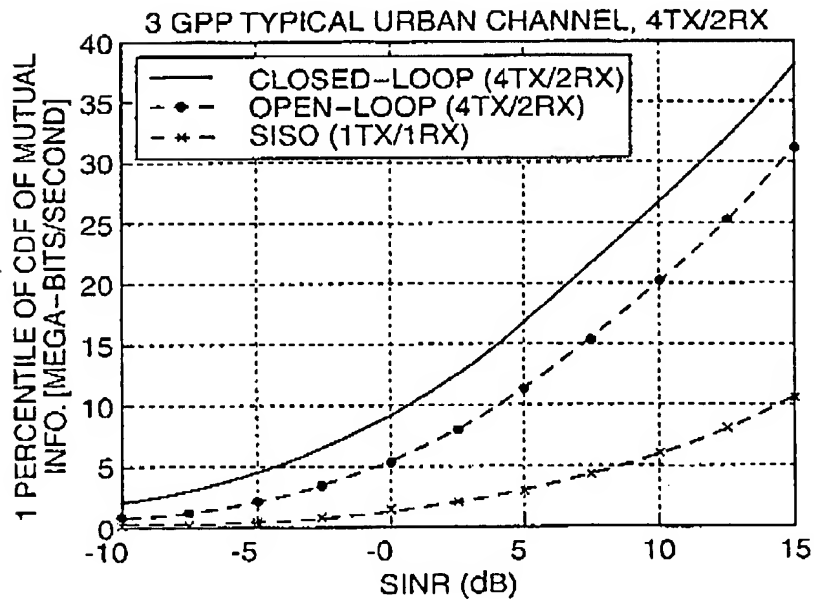
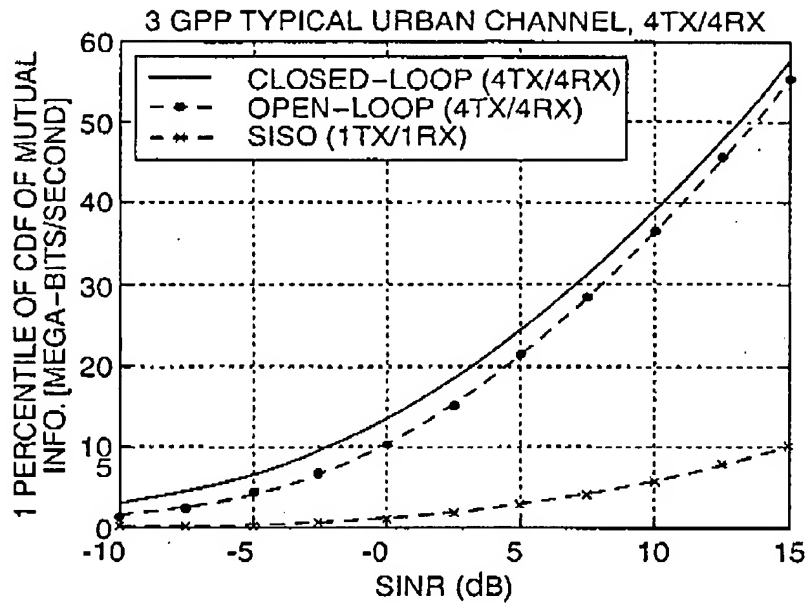


FIG. 3

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**FIG. 4**

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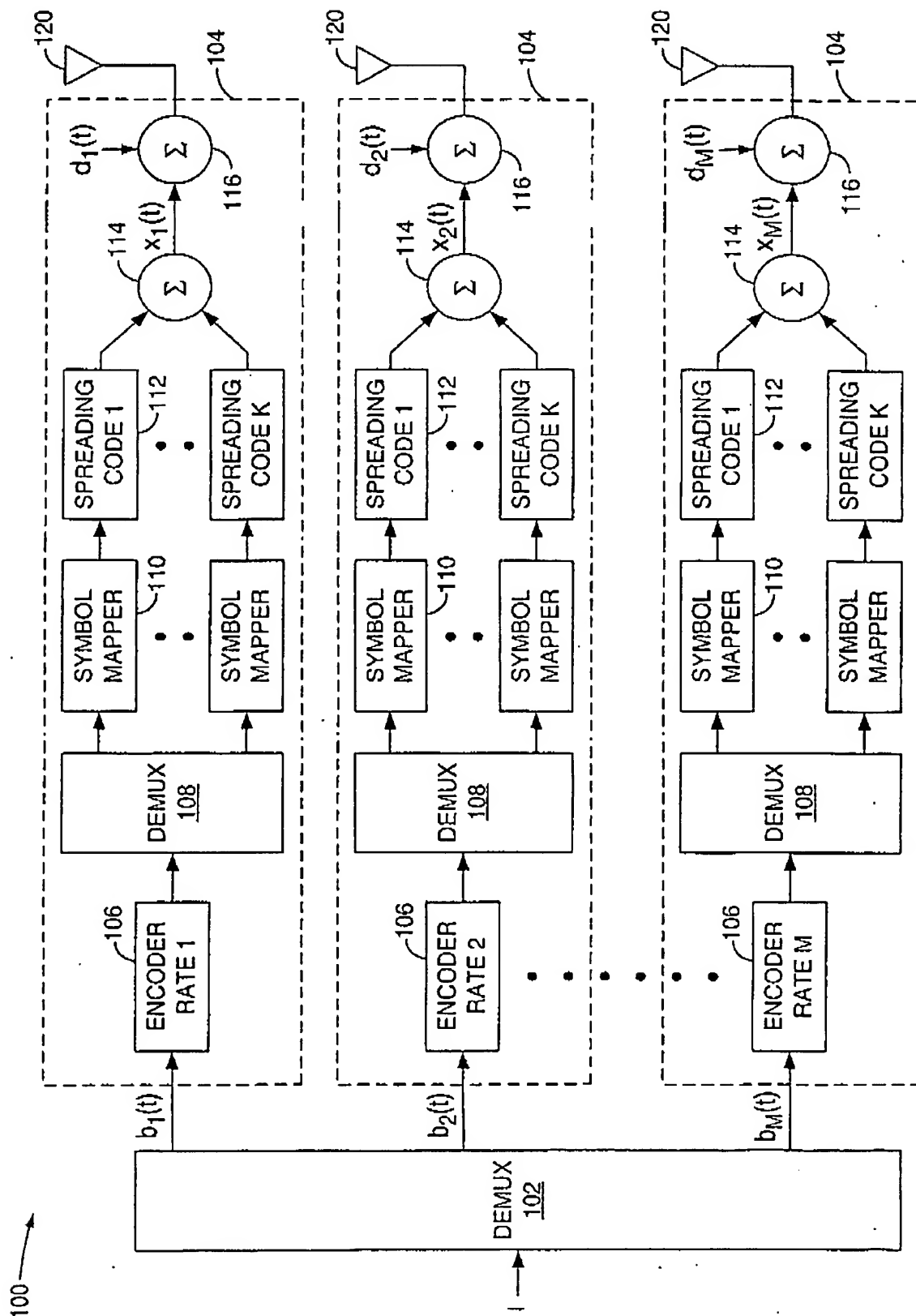


FIG. 5

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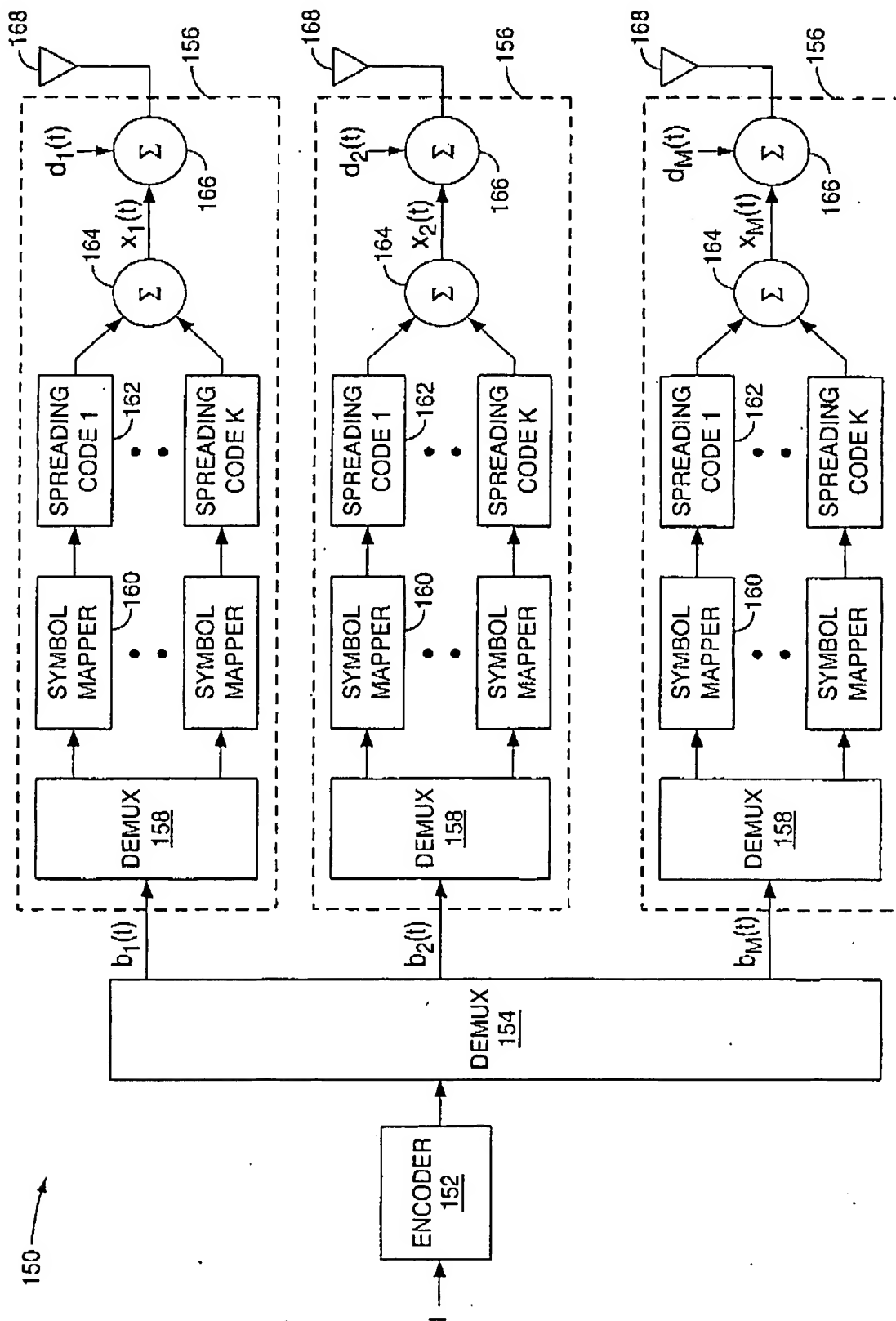


FIG. 6

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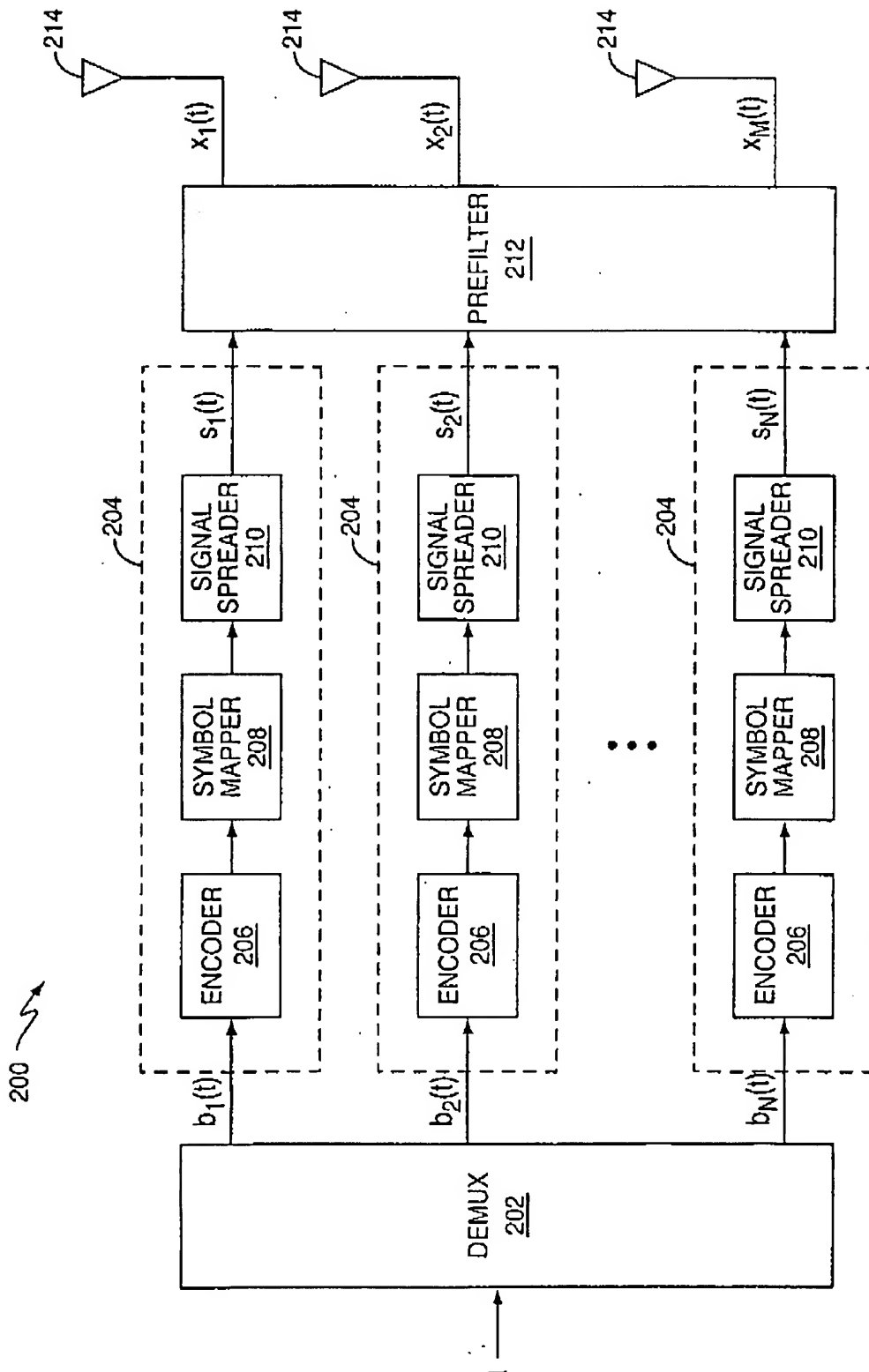


FIG. 7

## INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US2005/003944

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H04L1/06 H04L1/00

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

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X	EP 1 309 121 A (LUCENT TECHNOLOGIES INC) 7 May 2003 (2003-05-07) column 1, line 27 - line 44 column 3, line 17 - line 29 column 4, line 33 - line 52 column 5, line 14 - line 23 column 6, line 9 - line 15 column 6, line 50 - column 7, line 14 ----- -/--	1, 2, 4, 6, 30, 31, 34

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

26 April 2005

Date of mailing of the international search report

04/05/2005

Name and mailing address of the ISA

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## INTERNATIONAL SEARCH REPORT

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## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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